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CANYON WINDS AT HILL AIR FORCE BASE, UTAH

Richard Leland Eddy

Utah University
Salt Lake City, Utah

June 1957

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DEPARTMENT OF METEOROLOGY

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CANYON WINDS AT HILL AIR FORCE BASE, UTAH

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Department of Meteorology

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PROGRESS REPORT

on

THE EFFECT OF ATMOSPHERIC FLUORIDES ON MAN

Cooperating Agencies and Personnel

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INTRODUCTION

The easterly winds blowing out of the canyons along the west face of the Wasatch Range at times reach velocities which are hazardous to air traffic at airports near the mouths of these canyons. Not only do they hamper safe landing of aircraft but they also can cause extensive damage to parked aircraft. In winter, these strong winds can drift the snow over heavily traveled highways (U.S. Highways 30, 89, 91, plus several state highways). These strong east winds can also break tree limbs, topple flimsy constructions, and generally make life unpleasant while they are blowing.

The object of this study is to investigate those factors which influence easterly canyon winds when the velocity stays above 20 knots for several hours. The ultimate goal of any such study is to find a good forecasting technique.

Canyon breezes occur almost every night that the sky is clear or only partly cloudy. This is a result of the radiational cooling of the surface layer of air on the mountain slopes. Such breezes usually do not extend more than a few miles into the valleys and rarely reach excessive speeds. In fact, in summer these cool winds are a refreshing change from the heat of the day. Only when this nocturnal cooling process is reinforced by the large-scale circulation, do the winds reach large proportions. Favorable synoptic situations are a high atmospheric pressure area in Wyoming and/or a vigorous low pressure area in western or southern Utah or in Arizona or southern Nevada [18].

BASIC THEORY

Solenoids. It was shown by V. Bjerknes in 1898 that

$$\oint \dot{\vec{v}} \cdot \delta \vec{r} = -\oint \alpha \, \delta p.$$

This expression is known as the circulation theorem. It is one of the fundamental theorems for the study of physical hydrodynamics and is discussed in most texts on dynamic meteorology [13,16].

Another important concept in hydrodynamics is the theorem of solenoids,

$$-\oint \alpha \, \delta p = N_{\alpha,-p},$$

where $N_{\alpha,-p}$ is the algebraic number of solenoids contained within an arbitrary closed curve in the atmosphere.

Figure 1 is a cross-section of the atmosphere above a coast where the land surface is warmer than the ocean surface. Assuming that the air mass is stationary, the isobars would be nearly horizontal. But due to the differential heating at the surface, the isosteres would be inclined. The intersection of two unit isosteres with two unit isobars, as shown in Figure 1, forms a tube with parallelogrammatic cross-section. The contour ABCDA is known as a solenoid. This area is equal to the integral $-\oint \alpha \, \delta p$, which is the right hand term of the circulation theorem. The positive sense of the solenoid, and therefore the circulation, is taken as the right-handed rotation from the specific volume ascendent $\nabla\alpha$ to the pressure gradient $-\nabla p$ (through an angle less than 180°) [13,16].

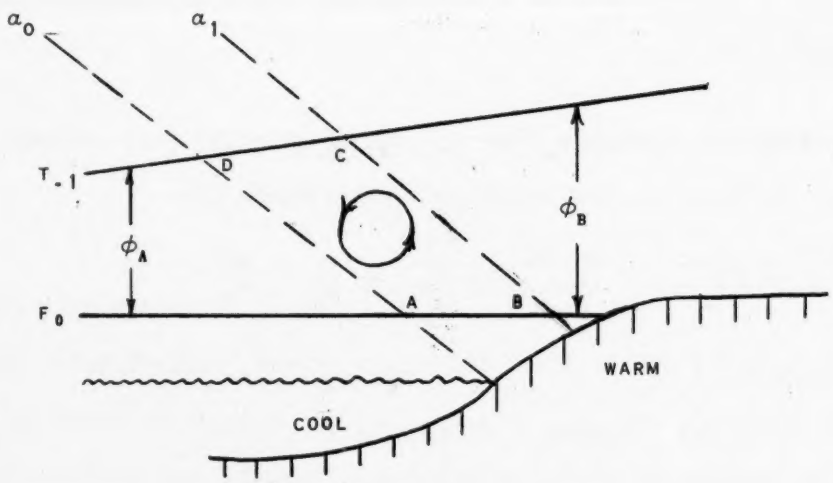

FIGURE 1. SCHEMATIC CROSS-SECTION OF THE ATMOSPHERE SHOWING ISOBARIC-ISOSTERIC SOLENOIDS AND RESULTING CIRCULATION (FROM STEWART [16]). (SLOPE OF ISOBARS SOMEWHAT EXAGGERATED.)

From the combination of the circulation theorem and the theorem of solenoids, the following equations are obtained:

$$\oint \dot{w} \cdot \delta r = N_{\alpha_1 - \rho} \qquad \text{or} \qquad \frac{D}{Dt} \oint w \cdot \delta r = N_{\alpha_1 - \rho}$$

But $\oint w \cdot \delta r = C$ (circulation integral 13).

Therefore, $\frac{DC}{Dt} = N_{\alpha_1 - \rho}$ (circulation acceleration).

It is seen that a decrease in solenoid number will decrease the change in circulation, but will not change the velocity directly. The velocity will increase until a negative change in circulation, i.e., solenoids of the opposite sense, develops.

The number of solenoids, $N_{\alpha_1 - \rho}$, can be obtained from several expressions. Perhaps the most convenient expressions are

$$|N_{\alpha_1 - \rho}| = R_d (T_{mB} - T_{mA}) \ln \frac{p_1}{p_2} = \phi_B - \phi_A$$ (see also Fig.1.),

where p_1 and p_2 refer to the lower and upper isobars, respectively, between two vertical sections, and T_{mA} and T_{mB} are the mean temperature of the colder and the warmer verticals, respectively, through the pressure layer. The dynamic thicknesses of the isobaric layer at the two verticals are represented by ϕ_A and ϕ_B. The concepts of solenoidal circulation are useful in explaining the mountain and valley winds.

Mountain and valley winds. One of the basic causes underlying the strong easterly canyon winds is the mountain and valley wind system. On nights with little or no cloudiness, the air on the mountain slope cools faster than that at the same level in the free atmosphere over the valley. This creates a temperature gradient directed toward the slope. The cold air, being more dense, sinks or contracts. The sinking of the air has no effect on the surface pressure at first, but pulls the isobars down, as shown in Fig.2. Since the density has increased, the specific volume has decreased, and the isosteres turn up. The air tends to flow in the direction of the height gradient of the isobaric surfaces; hence the air aloft flows toward the mountain slope, resulting in an accumulation of air above the slope. The greater mass of air will increase the surface pressure and the isobars will begin to turn up. However, the specific volume increases with height more rapidly than the pressure decreases, and the solenoidal circulation thus established is directed away from the slope in the lower layers and toward the slope aloft (Fig.3). This circulation results in a downslope wind which is called the mountain wind. The greater the temperature gradient, the greater the number of solenoids and the stronger the circulation, and vica versa. The circulation tends to destroy the solenoids, and it can be shown that when the slope ceases to cool, the circulation will soon stop. During the day, heating occurs and circulation of the opposite sense develops, resulting in an upslope wind, sometimes called the valley wind. The development of this thermally-induced circulation is greatly modified by the large-scale circulation,

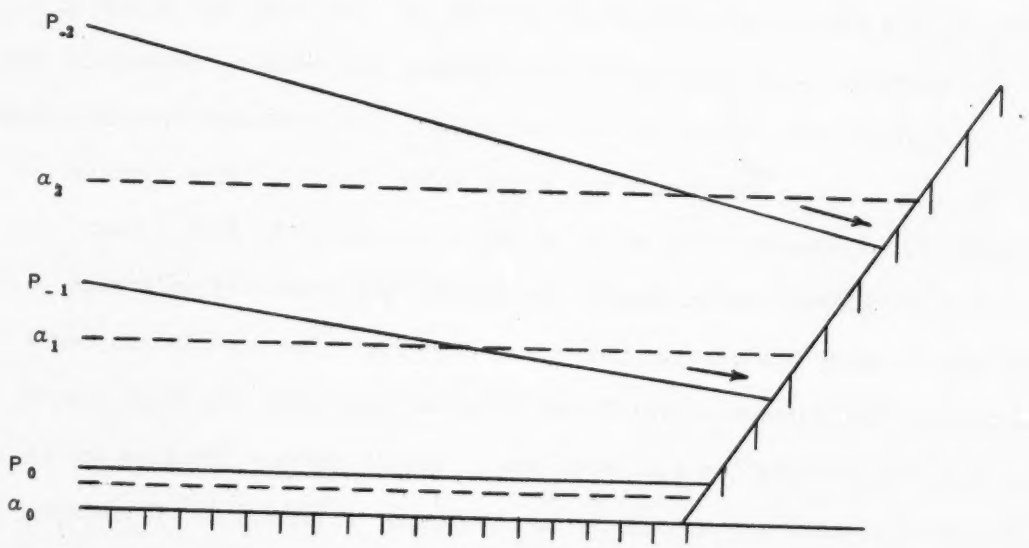

FIGURE 2. FIRST STAGE IN THE DEVELOPMENT OF THE MOUNTAIN BREEZE, SHOWING ONLY THE LOWER LAYERS. SURFACE CONDITIONS ARE UNCHANGED, AND AIR ALOFT FLOWS TOWARD SLOPE.

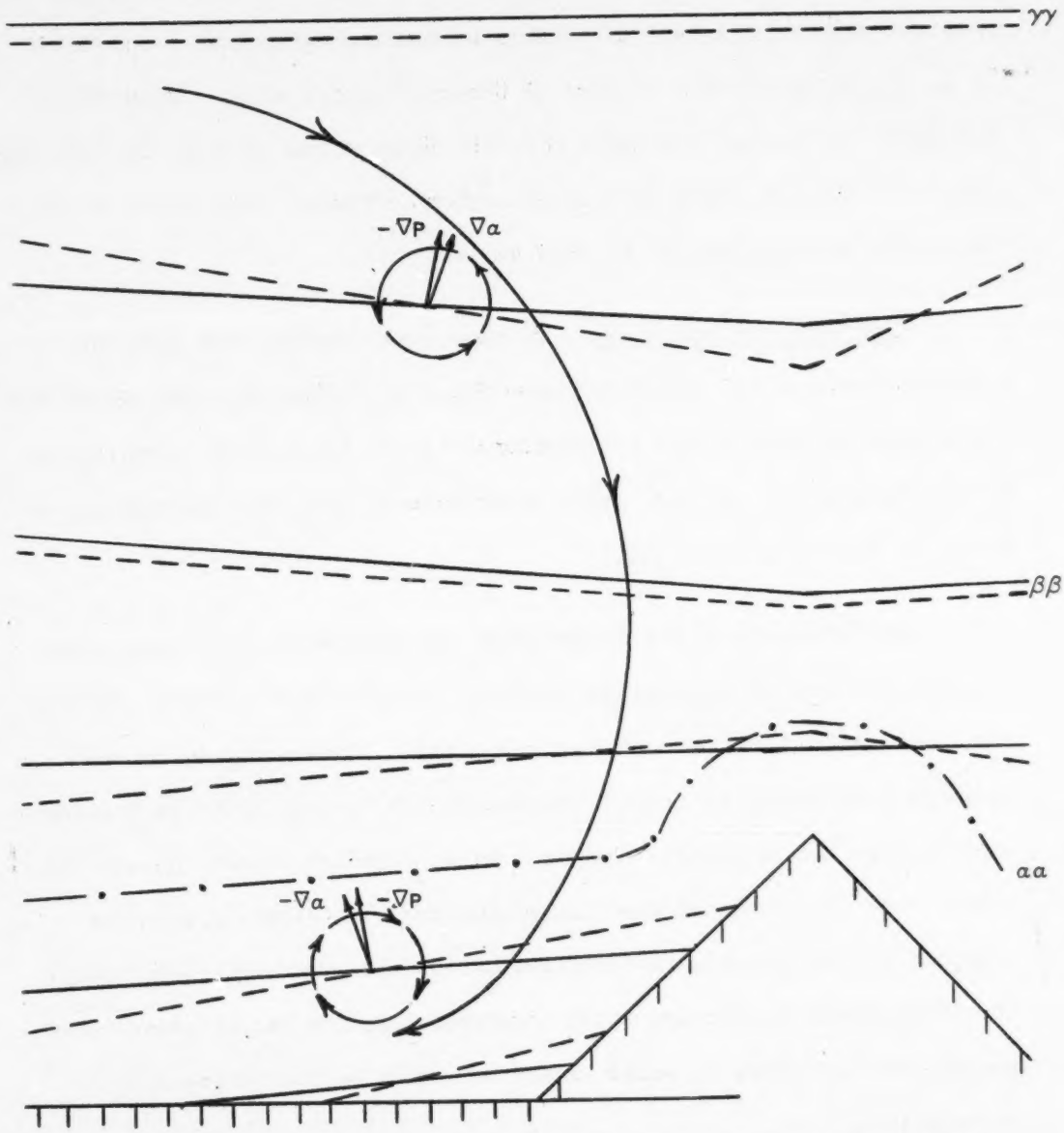

FIGURE 3. MOUNTAIN BREEZE CIRCULATION, SHOWING RETURN FLOW ALOFT. THE $\gamma\gamma$ SURFACE IS THE UPPER LIMIT OF THE CIRCULATION, THE $\beta\beta$ SURFACE MARKS THE UPPER LIMIT OF THE MOUNTAIN BREEZE ITSELF, AND THE $\alpha\alpha$ SURFACE IS WHERE THE CIRCULATION IS PURELY VERTICAL. FOR A COMPLEGE DISCUSSION OF THIS CIRCULATION SEE GODSKE, ET AL [9].

and will usually not be detected readily unless the large-scale pressure gradients are weak.

Now extend the concepts of the thermally-generated circulation from the single slope case of relatively small geographical proportions to an air drainage basin of several thousand square miles. When only a few major outlets are available for this large volume of air, the outlets, i.e., the canyons, cause pronounced venturi effects. The result is the relatively strong wind out of each canyon mouth.

Large-scale circulation. It has already been stated that the mountain breeze will not extend more than a few miles into the valley nor reach high speedsunless it is reinforced by the large-scale circulation. Favorable synoptic patterns are a high pressure area over Wyoming and/or a low in Utah or Arizona [18].

The influence of the large-scale circulation on the canyon winds can best be seen by examination of Fig.4. Fig.4 shows a canyon oriented east-west, with a north-south mountain ridge. A high, a low, or both pressure centers may be present in nature. It is seen that the gradient wind is from the southeast; however surface friction causes the wind to blow across the isobars toward lower pressure, and directly down the canyon. If the mountain breeze circulation were present at this time, the large-scale circulation would reinforce it; if a valley breeze were present at this time, it would likely be hidden by the large-scale circulation.

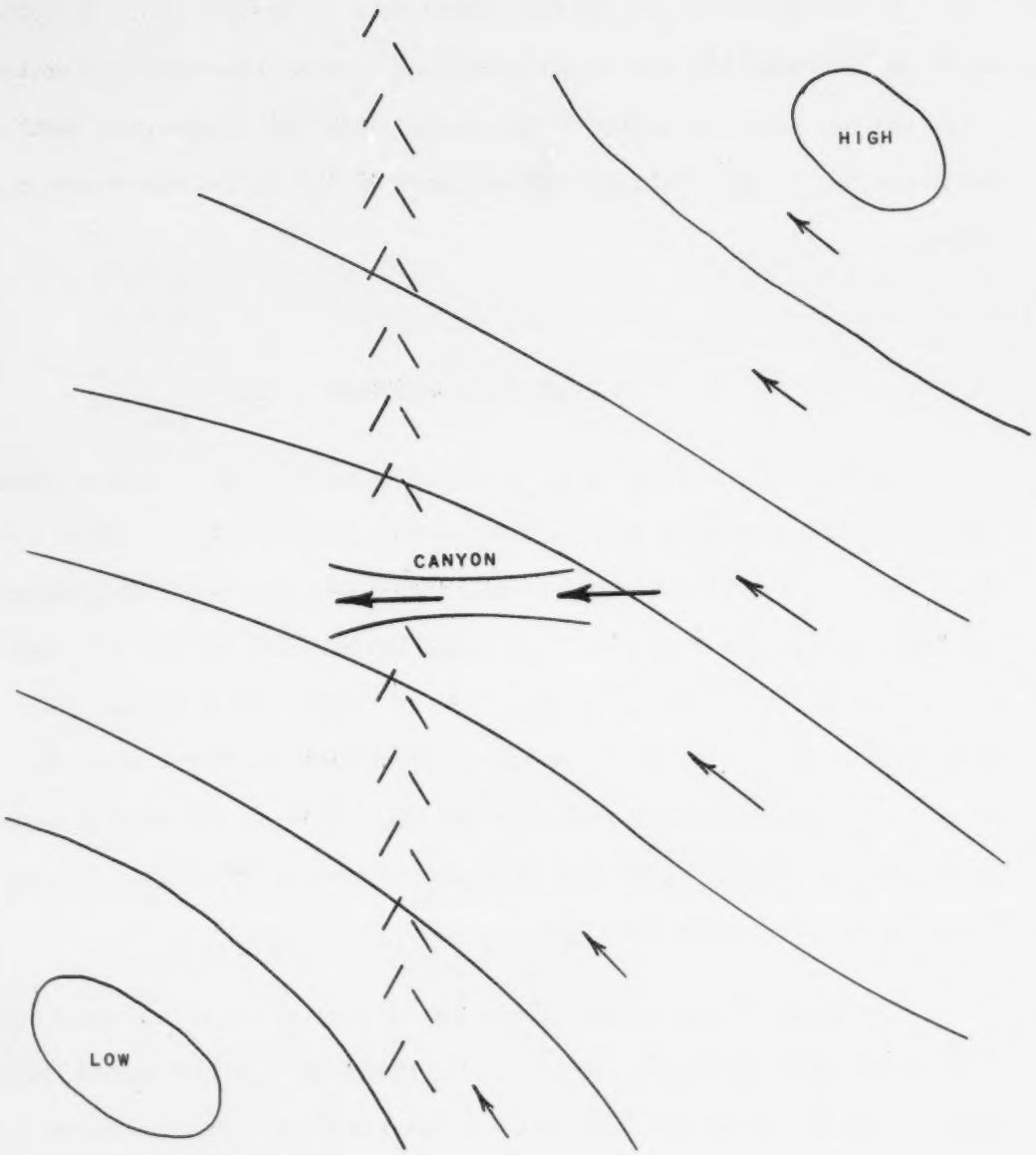

FIGURE 4. INFLUENCE OF LARGE-SCALE CIRCULATION ON CANYON WINDS. CANYON WITH EAST-WEST ORIENTATION, SHOWING GRADIENT WIND (LIGHT ARROWS) AND FRICTIONAL DEVIATION FROM GRADIENT (HEAVY ARROWS).

If the synoptic pattern described above is present aloft as well as at the surface, the east winds will tend also to blow over the mountain ridge and out into the valley to the west. Thus the large-scale east winds are not always confined to the canyon mouths as are the mountain winds.

TOPOGRAPHICAL FEATURES

Hill Air Force Base, Utah, was used in this study of canyon winds because of the proximity of this station to a typical canyon. Hill Air Force Base is located four and one-half miles west of the Wasatch Mountains and the mouth of Weber Canyon at an elevation of 4788 ft. MSL on a small plateau about 300 ft. above the main valley floor. The mountains rise steeply from the valley floor, which is about 4570 ft. above mean sea level[1], to an average height of 8500 ft. MSL. East of the Wasatch Range is the plateau region of eastern Utah and western Wyoming, with an average elevation of about 7500 ft. [14].

The Weber Canyon is one of the few canyons which pass completely through the Wasatch Range. It has an air drainage basin of approximately 6000 sq. miles. With the 2500-3000 ft. drop and the large volume of air involved, it can be seen why the forecasting of the high velocity canyon

---

1. The valley referred to here is only one part of the Great Salt Lake Valley, which has an average elevation of 4250 ft. MSL.

winds is a difficult but interesting problem. If the general circulation is superimposed upon this drainage wind, the problem becomes that much more complicated.

West of Hill Air Force Base is the famous Great Salt Lake. Since data are not available at this time, no attempt has been made in this study to use the lake temperature as a factor in the east wind system.

PROCEDURE

General. Data from the years 1953-1955 were used in this study of easterly canyon winds. The Daily Upper Air Bulletins, published by the U.S. Weather Bureau, served as the source of information for the radiosonde data for 1953 and 1955. Surface and upper air data for 1954 were taken from microfilmed copies of WBAN 10A and B and WBAN 31A and B, respectively. The wind data were taken from the surface observation forms (WBAN 10A and B) at Hill Air Force Base and not from the continuous recording wind charts. Therefore, the winds used in the study are the one-minute or five-minute average winds at the time of the observation (approximately 30 minutes past the hour). The gustiness reported is the peak speed of gusts observed during the fifteen minutes before the observation is taken. Special observations of wind are taken whenever there is a wind shift or a sudden doubling of speed (over a one-minute interval) to more than 30 miles per hour (26 knots) [17].

Thunderstorm days in the months of May through September were compared with those days having strong east winds. Any strong wind which occurred near the time of a thunderstorm would probably be associated with such disturbance and would have no relationship with the factors used in this study. Therefore, those strong east winds which were reported while thunderstorms were present have not been included in this study.

Diurnal distribution. A frequency distribution of the time of occurrence of 339 cases of east winds 20 knots and higher shows the mean at 0218 Mountain Standard Time, and the median at 0306 MST (Fig.5). The standard deviation of the distribution is 3.78 hours. The standard deviation was computed even though this distribution is not quite normal; it is the opinion of the author that the occurrence of these winds would show a normal distribution if enough samples were available. Of the observed cases, 89% occurred between 2000M and 0800M; 81% of the cases occurred between 2100M and 0700M. This distribution indicates that easterly winds are almost exclusively a night-time feature. This in itself is a valuable piece of forecasting information because it implies that, whatever the cause, east winds are not likely to begin until evening. The exceptions would be particularly strong large-scale circulation patterns of the type shown in Fig.4.

Radiosonde data - Hill Air Force Base-Lander. A graph of maximum wind speed vs. 850 mb height gradient between Hill Air Force Base and Lander, Wyoming (Hill Air Force Base minus Lander) was plotted for

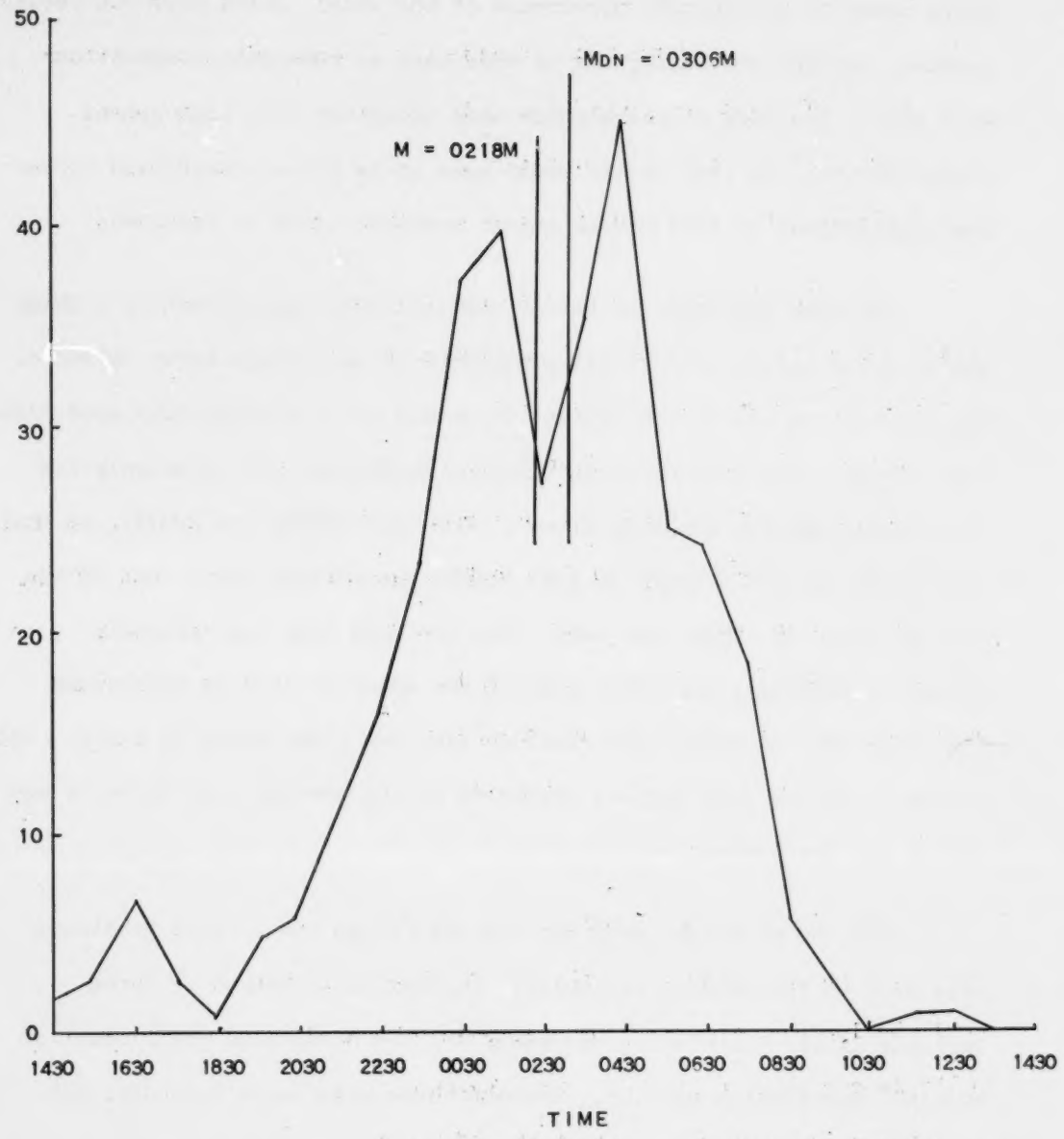

FIGURE 5. FREQUENCY DISTRIBUTION OF TIME OF OCCURRENCE OF EAST WIND OF 20 KNOTS OR HIGHER.

graphical correlation, using the 0800M (1500Z) radiosonde data 6 to 26 hours prior to the initial occurrence of the wind. There were 104 cases plotted, but the scattering was so wide that no numerical computations were made. The lack of correlation when using the wide time spread suggested that the time factor would have to be better controlled before the significance of this 850 mb height gradient could be assigned.

The time lag could be better controlled by taking that raob which was 12 hours before the initial occurrence of east winds above 20 knots. The 12-hour lag was chosen because it seemed to be a reasonably good forecast period. The frequency distribution indicates that relatively few cases begin exactly 12 hours after a raob time (0800M and 2000M), so that raob which was 12 ± 6 hours or less before the initial occurrence of the wind 20 knots or higher was used. The variable time lag naturally presented problems, but since most of the stations used in this study take only two radiosonde observations each day - one every 12 hours - this seemed to be the only logical procedure if the results were to be of any use to the forecaster.

The 850 mb height gradient and the 700 mb temperature gradients were used as independent variables. The Doolittle method of three variable linear correlation was used, and the unadjusted coefficient of multiple correlation was .05. Seventy-three cases were included, but this value is not significant at the 5% level.

Since Lander (5563 ft.) is somewhat above the 850 mb surface (about 5000 ft.), the 700 mb height (about 10,000 ft.) gradients were tried. Using the 12 $\pm$ 6 hour time lag and 63 cases, the unadjusted coefficient of simple linear correlation was -.02. This is not significant at the 5% level.

It was thought that the elimination of those winds below 30 knots might improve the correlation between wind speed and 850 mb height gradient. Only 30 cases were available, however, and the unadjusted value of -.31 is not significantly different from zero at the 5% level, although it is in the right direction.

The number of solenoids is an important factor in the mountain and valley breeze and might also be important in east winds caused by the large-scale circulation. A measure of the number of solenoids between two stations can be obtained by taking the difference between the 700 mb height minus the 850 mb height for the two stations (see page 4). The values were taken from raob data 12 $\pm$ 6 hours before the initial occurrence of the strong east winds. These differences were plotted against wind speed, both average and peak gusts. A total of 86 cases was used. No numerical computations were performed, but the scattering of data suggested low correlation, if any. The data were then separated into seasons, and although the number of cases in each season was too small to obtain statistically significant results, it appeared that only the spring season (April, May and June) had even a moderate correlation.

Radiosonde data - Hill Air Force Base-Ely. The linear correlation between wind speeds of 20 knots and higher and the 850 mb height gradients for Hill Air Force Base minus Ely, Nevada, was -.07, using 65 cases. This value is not significant at the 5% significance level. The use of the 700 mb height gradients gave a correlation coefficient, corrected for loss of degrees of freedom, of .39. This value is significantly different from zero above the 1% level of significance. It was thought that the addition of the 700 mb temperature gradient and the elimination of winds below 25 knots might improve the correlation. Only 35 cases were available, but the adjusted coefficient of multiple correlation was .58. This value is significant at the 1% level.

Radiosonde data - Hill Air Force Base-Las Vegas. The 700 mb height differences between Hill Air Force Base and Las Vegas, Nevada, were tested. The adjusted coefficient of correlation for 37 cases was .28. This value is not significantly different from zero at the 5% level. The 850 mb height gradients were not used because of the lack of success with Lander and Ely 850 mb data.

Radiosonde data - Hill Air Force Base-Lander-Grand Junction. The orientation of the isobars or pressure height contours, as well as the existence of a high pressure area in Wyoming, seems to be important in the study of canyon winds. The use of the 850 mb height gradients between Hill Air Force Base and Lander and Grand Junction, Colorado, should give an indication of the orientation of these lines. Radiosonde data 12 ± 6 hours before the onset of the strong winds were used, as before, and wind

speeds of less than 25 knots were not considered. Using 39 cases, the adjusted coefficient of multiple correlation was .46, which is significant at the 1% level. However, this gave no better results than the previous tests.

WBAN 10 data - 850 mb height correlation. Because the computed 850 mb heights appearing on the Weather Bureau surface observation form (WBAN 10A and B) are available at 3-hour intervals, the use of these data would reduce the variation in time lag from $\pm$ 6 hours to $\pm$ 1 hour. The 850 mb height gradients for Hill Air Force Base minus Rock Springs, Wyoming, Ely and Grand Junction were examined, using 44 cases of wind above 25 knots. With a 12 $\pm$ 1 hour time lag, the coefficient of multiple correlation was .12, but when corrected for loss of degrees of freedom it fell to zero.

WBAN 10 data - Hill Air Force Base-Rock Springs. As the use of time-lagged data did not yield satisfactory results, concurrent data from WBAN 10A and B were used. In order to make the results of use to the forecaster, the study was limited to those pressure and temperature parameters from WBAN 10A and B which appear on the circuit A teletype network, i.e., sea level pressure, 850 mb height, altimeter setting, and station temperature. The sea level pressure is usually considered to be quite fictitious in the Mountain West. The 850 mb height is based on standard pressure and the mean virtual temperature, estimated by a procedure involving the temperature 6 years previously. The 850 mb height is approximately 5000 ft. so that as station altitudes deviate from this height, the

data are increasingly fictitious. Weather Bureau Circular N [17] gives a complete discussion of these pressure computations. Also, the 850 mb heights are reported only at 3-hour intervals. For these reasons, the 850 mb height was not satisfactory for this phase of the study.

The altimeter setting is that pressure which will cause aircraft altimeters to read the true altitude of the field when the aircraft is on the runway. It is sometimes called the standard atmospheric sea-level pressure, and its computation is independent of temperature [17]. Therefore, the altimeter setting was chosen as the measurement of pressure.

Because of its location on the Wyoming plateau and since it is the only station near the head of the Weber Canyon drainage area which operates 24 hours a day, Rock Springs was chosen as the first station in this analysis. Graphs were made of wind speed, both average and maximum (peak gusts), against altimeter setting gradient for 13 selected cases in 1954. These cases had east winds blowing for at least 12 hours. The graphical correlations for these cases ranged from moderately high (the order of .8) to essentially zero.

An examination of several cases which were definitely caused by large-scale circulation suggested that if time were considered, a rather interesting curve resulted. The east winds began with some given gradient, which varied from case to case; increased in speed as the pressure gradient increased; reached a peak; fluctuated for several hours with little change in pressure gradient, due probably to the thermal circulation; and then decreased as the pressure gradient decreased (Fig.6). Several interesting

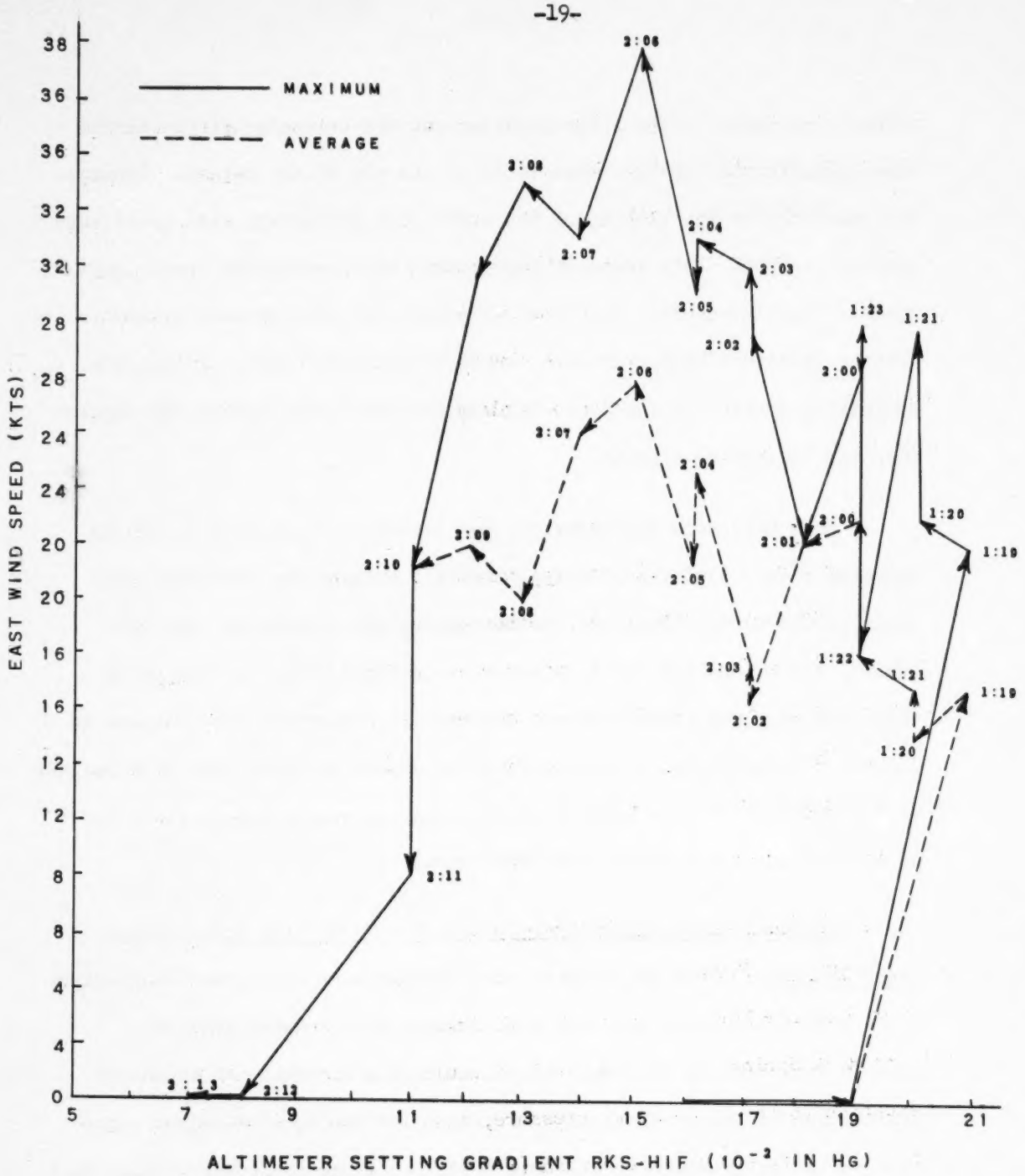

FIGURE 6. CURVE SHOWING TIME DEPENDENCY OF WIND SPEED-ALTIMETER SETTING GRADIENT RELATIONSHIP (1 NOVEMBER 1630M TO 2 NOVEMBER 1330M, 1954).

things were noted. First, the gradients at the beginning of the period were significantly greater than those at the end of the period. Second, the gradients on the section of the curve with increasing wind speed were generally greater than those on the section with decreasing speed, suggesting that increasing wind speed is associated with greater altimeter setting gradients than decreasing winds of the same speed. Third, the decreasing section of the curve was almost always more smooth and regular than the increasing section.

When this time consideration was extended to the rest of the 13 selected cases, 9 of the 13 did not exhibit those three features. The cases in the months from April to September, and especially July and August, did not follow the original curve pattern (Fig.6). The cases which did show the three features occurred in the months from October to January. In a few cases the selection of a station other than Rock Springs gave results which were similar to the original curve, but in other cases no station was found which gave those results.

Altimeter setting gradients - Hill Air Force Base-Rock Springs-Grand Junction. From geostrophic considerations, a weak pressure gradient between Hill Air Force Base and Rock Springs and a strong gradient between Rock Springs and Grand Junction would give northwest-southeast orientation to the isolines of pressure, and a strong down-canyon component to the large-scale circulation (Fig.7). It is important to note that a small change in the orientation, and therefore in the pressure gradients, can result in a relatively large change in the down-canyon component.

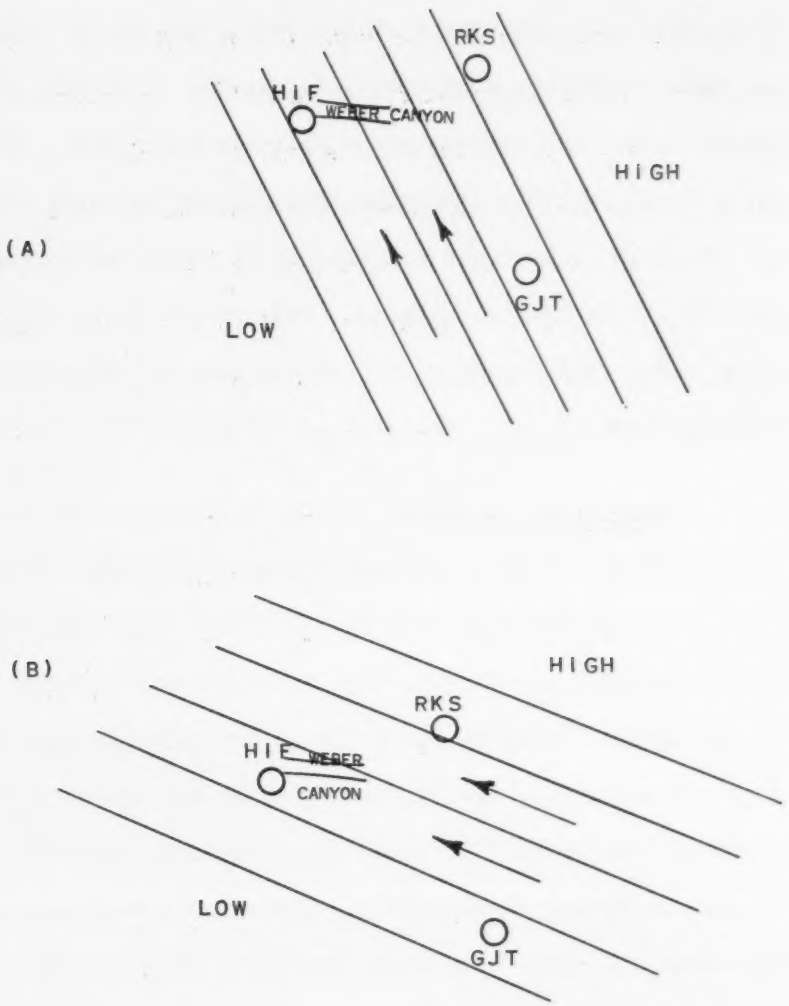

FIGURE 7. ORIENTATION OF ISOLINES OF PRESSURE WITH RESPECT TO WEBER CANYON:

(A) WEAK DOWN-CANYON GEOSTROPHIC FLOW

(B) STRONG DOWN-CANYON GEOSTROPHIC FLOW.

This fact can complicate a statistical study of the orientation. A graph was made of maximum wind speed against the concurrent altimeter setting gradient for Rock Springs minus Hill Air Force Base. The Rock Springs minus Grand Junction gradients were plotted on their corresponding points on the graph so that the graph could be subjected to three variable graphical correlation analysis. This showed little correlation. Sixty cases had a coefficient of multiple linear correlation of .28 (adjusted value), which is not significantly different from zero at the 5% level.

Time series analysis. A time series analysis of wind speed and of corresponding altimeter setting gradients for Rock Springs minus Hill Air Force Base and Rawlins minus Hill Air Force Base was made of five cases in which the duration of east winds was at least 24 hours (Fig.8 is an example of one case). These analyses showed that the stronger the maximum reported peak gust, the shorter the time lag after the maximum pressure gradient (see Table I). These five cases all occurred in the period October to March. A similar relationship is sometimes observed with the Ely minus Hill Air Force Base, Las Vegas minus Hill Air Force Base, Elko minus Hill Air Force Base, and Grand Junction minus Hill Air Force Base altimeter setting gradients.

TABLE I

TIME LAG BETWEEN WIND SPEED AND PRESSURE GRADIENT MAXIMA FOR FIVE CASES IN 1954 and 1957

Peak wind speed (knots)	36	36	47	47	55
Time lag after maximum gradient (hours)	10	10	7	5	7

FIGURE 8. TIME RELATIONSHIP BETWEEN ALTIMETER SETTING GRADIENTS AND WIND SPEED (24-25 OCTOBER, 1954).

Another point should be brought out concerning these time series. There was considerable variation in the magnitude of the gradients from case to case. The initial value of the Rawlins-Hill Air Force Base gradient varies from -.04 inches Hg in one case to +.22 inches Hg in another, or a range of almost 9 mb. The variation of maximum values amounted to .15 inches Hg, or slightly more than 5 mb.

High and low-pressure center indexing. It is assumed that a high pressure area in Wyoming and/or a vigorous low in Utah or Arizona are synoptic features associated with strong canyon winds. A more precise examination of the relation between the winds observed and the precise position of the pressure centers is desirable. The Western United States could be subdivided into smaller regions, using a procedure similar to that of Multanovsky [15], in order to study the distribution of the pressure centers associated with the canyon winds. Figures 9a and 9b show such a subdivision. Table II gives the boundaries of each region.

TABLE II

BOUNDARIES OF HIGH AND LOW-INDEX AREAS

		West Longitude	North Latitude
Index	1	107-112	43-55
	2	97-107	43-55
	3	97-107	35-43
	4	107-112	35-43
	5	112-125	43-55
	6	112-125	37-43
	7	120-130	37-43
	8	115-120	37-43
	9	110-115	37-43
	10	105-110	37-43
	11	120-130	25-37
	12	115-120	25-37
	13	110-115	25-37
	14	100-110	25-37

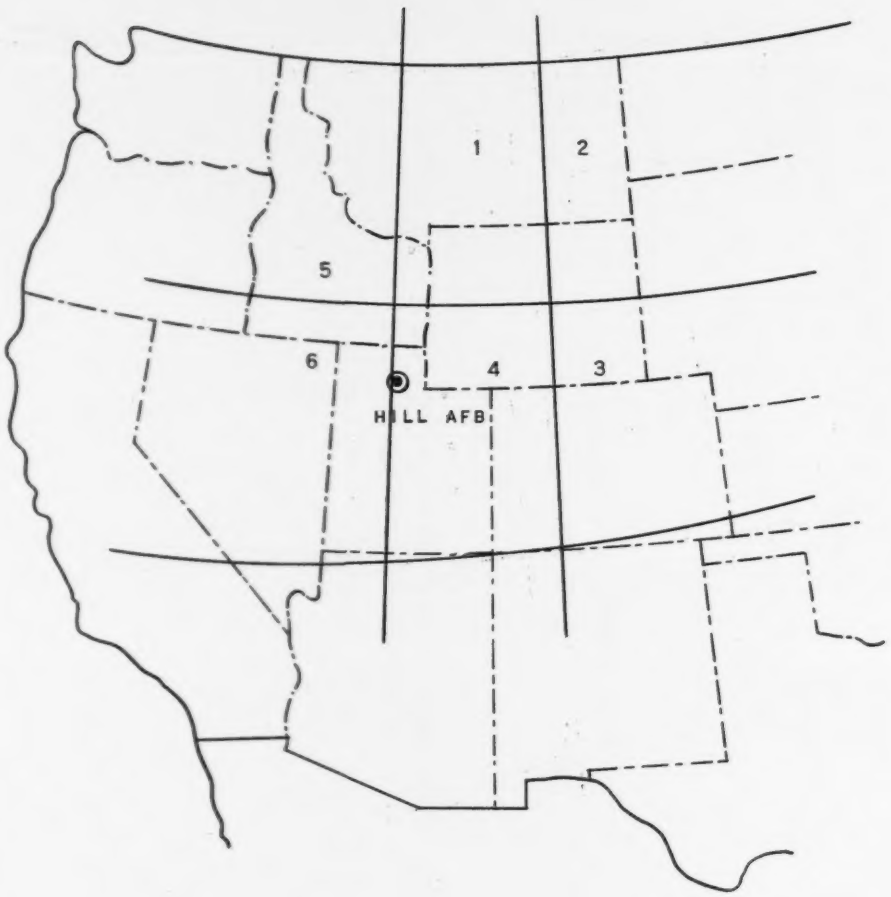

FIGURE 9A. HIGH INDEX AREAS.

FIGURE 9B. LOW INDEX AREAS.

The six-hourly synoptic maps for 1954 and 1955, as analyzed by the personnel of the Weather Bureau's Salt Lake Airport Office, were used in the indexing procedure.

The distribution of cases in each sub-area was made for the 13 selected cases in 1954. The positions of the centers were noted each time an east wind was reported at or within one hour of the map time (0530, 1130, 1730, 2330 MST). The high and low centers were tabulated according to their index position. If two or more distinct pressure centers of either type were present on a single synoptic map, each was entered. This distribution was independent of wind speed, time of day, and season (see Table III). Distributions of cases near the onset of the strong winds and near the time of the maximum were also examined. When cases for all months were used, regions 12 and 13 had especially high frequencies. These regions, however, are in the area of the thermal low, so characteristic of the southwestern summer synoptic patterns. This thermal low is usually quite shallow and probably has little effect on the canyon winds. When only the months of October through March were used, the distributions showed a predominance of high pressure areas in regions 1 and 3, and a large number of lows in region 13 (see Tables IV-VI).

Tables V and VI are probably the most representative of the large-scale circulation patterns when strong canyon winds occur. Both distributions show a predominance of high pressure areas in regions 1 and 3, and a particularly large number of lows in region 13.

TABLE III

INDEX DISTRIBUTION FOR THE 13 SELECTED CASES IN 1954

	High						Low							
Index	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Frequency	8	2	12	11	5	0	6	4	4	6	6	19	29	6

TABLE IV

INDEX DISTRIBUTION NEAR START OF STRONG WINDS FOR CASES IN 1954, 1955 AND 2 CASES IN 1957 (6 hours duration or more).

	High						Low							
Index	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Frequency	12	6	13	9	4	3	2	3	5	3	2	18	39	0

TABLE V

INDEX DISTRIBUTION NEAR ONSET OF STRONG WINDS, OCTOBER-MARCH OF 1954, 1955, JANUARY 1957, AND MARCH 1957

	High						Low							
Index	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Frequency	4	1	7	3	2	0	2	1	1	0	1	4	12	0

TABLE VI

INDEX DISTRIBUTION NEAR TIME OF MAXIMUM SPEED, SAME CASES AS TABLE IV

	High						Low							
Index	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Frequency	5	3	8	4	4	0	3	0	1	0	2	3	12	1

A concurrent study of the positions of highs and lows, i.e., the number of $High_1$ and Low_{13}, $High_2$ and Low_{12}, etc., was made of 16 cases in which the east wind blew for at least 12 hours. Nothing conclusive could be drawn from this, due to the small number of cases, but the idea would certainly be worthy of future work.

INTERPRETATION OF RESULTS

Perhaps the most significant cause for the unsatisfactory forecasting results of this study lies in the difficulty of differentiating between mountain and valley winds and winds caused by the large-scale circulation. When they are distinct, winds of the mountain and valley breeze type have no relationship to the large-scale circulation; therefore the gradients as used in this study would have little bearing on their magnitude. The large-scale circulation can, of course, intensify or completely mask the mountain and valley winds, but it is usually rather weak when the mountain and valley winds are blowing. This complicates the problem of correlating wind speed with other parameters.

The greater diurnal temperature variations, less cloud cover, and generally weaker large-scale circulation in summer are conducive to mountain and valley breezes. It is probable that the majority of cases of east winds of 20 knots and higher, especially in the summer, are mountain winds and not directly related to pressure and temperature gradients on the synoptic scale.

For more satisfactory results, a seasonal separation of data is necessary. The mountain breeze is more prominant in the warm months, and the variations in vegetation and friction from one season to another might well be important. The use of trees and shrubs as windbreaks has been recognized for a long time, and the foliage raises the maximum wind speed to a higher level above the ground [6]. In winter, a snow cover offers less frictional resistance to the wind; in summer, the rugged terrain of the area increases the turbulence of the air [16].

The wide variability of the time lag, especially with regard to the radiosonde data (6-18 hour lag), is probably one of the primary reasons why the use of lagged data did not prove successful for a forecasting procedure. The inverse relationship between maximum wind speed and the time lag after the maximum pressure gradient (Table I) also supports this idea. Unfortunately, the meteorologist is forced to use that information which is available and not that which he would like.

The inconsistency of the type of the curve shown in Fig.6, i.e., stronger pressure gradients associated with increasing east winds than with decreasing winds of the same speed, suggests that no single pair of stations is always representative of the pressure system. This is one more argument in favor of developing an indexing system. The failure of the pressure gradient-wind speed relation to be present on any of those cases from May to September can, in part, be attributed to the increasing importance of the thermal circulation.

The findings of the entire study indicate that none of the stations as used here will yield satisfactory forecasting results. The positions of the pressure centers are rather variable, and any given gradient can be associated with a wide range of wind speeds. Since a high or low pressure area, or just thermal considerations, can be the cause of east winds greater than 20 knots, no single pair of stations can always indicate the onset of these strong winds.

The ability of the forecaster to make a subjective forecast of strong east winds lies in his being able to select and weigh each and every parameter, and base his forecast on those parameters which he feels are most significant at that time.

CASE STUDY: 25-27 January 1957

In January 1957, there occurred an example of strong canyon winds due to the large-scale circulation pattern. Since this was such a good example of reinforcement of canyon winds by the large-scale wind pattern, and as the data were readily available, it is included here as a case study. The case study was not made for the purpose of drawing definite conclusions. Rather, it was used to examine the application of the basic theory.

From 2030 MST on 25 January 1957 until 1430M on the 27th, Hill Air Force Base and the valleys of northwestern Utah experienced strong canyon winds. Gusts above 55 knots were recorded by the Hill Air Force Base anemometer. Beginning at 1130M on 24 January, 850 mb maps were plotted

from the three hourly data. Twenty-five maps, covering a span of 72 hours, were analyzed for the positions of high and low pressure centers. A high pressure area was primarily centered north-northeast of Hill Air Force Base and northwest of Lander, Wyoming, and was present on all of the maps. At 2030M on the 24th, 24 hours before the east winds began, a low pressure trough was present over Washington and Oregon and extended as far south as Battle Mountain, Nevada, and Burley, Idaho. This trough slowly drifted south, and by 1430M on the 24th a distinct low pressure center was located over Fallon, Nevada. At 1730M it was over Austin, Nevada; by 2030M it was just west of Tonopah, Nevada. This marked the time of the initial occurrence of east winds at Hill Air Force Base - 16 knots (see Fig.10). The high pressure center was located slightly east of West Yellowstone, Montana. At 2030M on the 24th, the low center was southeast of Tonopah, and the high center was still near West Yellowstone. The winds were now above the 20 knot level. The low center, with its accompanying fronts, continued to move southeastward, while the high center meandered over northwestern Wyoming.

By the afternoon of the 26th, the average wind speeds were 30-35 knots with gusts of 50-60 knots. The low pressure center was between Las Vegas, Nevada, and Cedar City, Utah, during this time; the high pressure center was elongated, extending from Butte, Montana, to Casper, Wyoming (Fig.11). As the low moved off toward the southeast, the average winds decreased somewhat, but the gusts were still above 50 knots. By 0830M on the 27th, the low pressure center was no longer distinct, but a

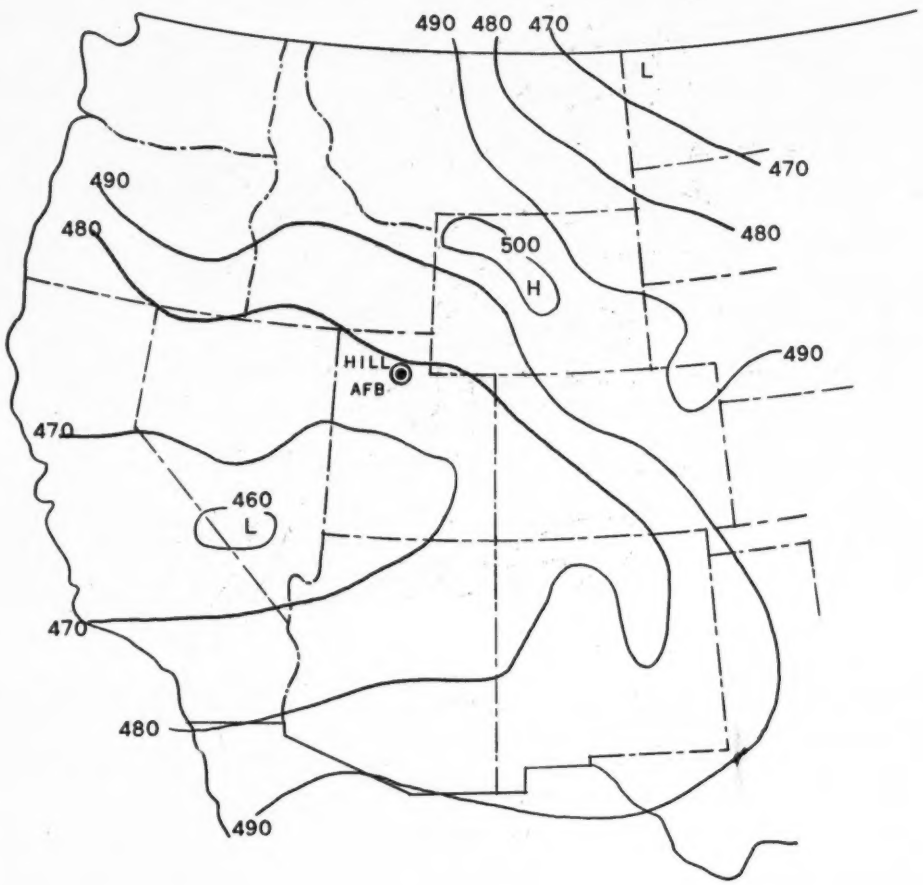

FIGURE 10. FIRST OCCURRENCE OF EAST WINDS. 850 MB CHART FOR 25 JANUARY 1957. 2030M.

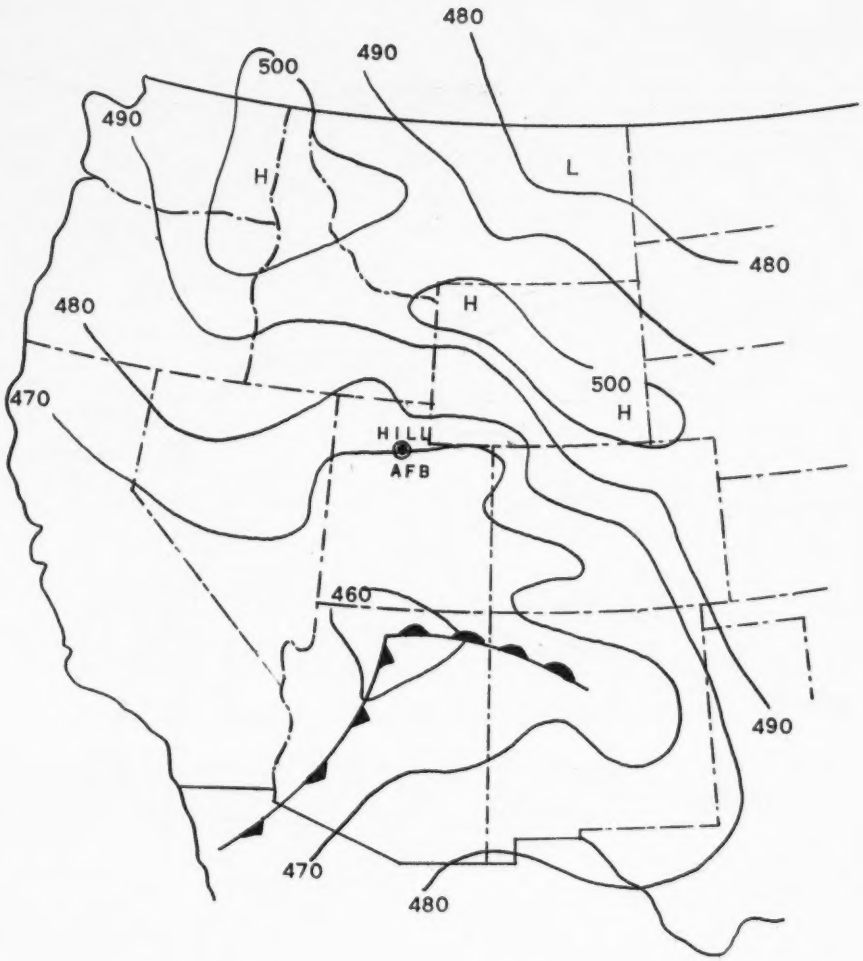

FIGURE 11. NEAR TIME OF MAXIMUM GUSTS. 850 MB CHART FOR 26 JANUARY, 1957. 1739M.

trough was still present in northern Arizona. However, an area of low pressure had developed over Hill Air Force Base, with the high centered over West Yellowstone (Fig.12). After 0830M the winds rapidly decreased, and by 1730M on the 27th the wind was calm. Figure 13 shows the positions of the pressure centers at 6-hourly (MST) intervals.

It is interesting to note that the maximum easterly canyon winds occurred near the time of the normal maximum valley (up-slope) winds. At that time, however, Hill Air Force Base was reporting broken to overcast skies with stratocumulus and/or altocumulus-type clouds. Therefore, the valley wind would not have been well developed.

The first step in the study of this case was to show the time distribution of the east winds, both average and peak gusts (Fig.14). The time distribution of variations in cloud cover was also examined, but since the sky was predominantly broken to overcast with low and middle clouds it was thought that this factor was of little significance in this case.

Graphs were constructed with wind speed plotted against concurrent gradients of sea level pressure, 850 mb height, altimeter setting and station temperature for Rock Springs minus Hill Air Force Base. The temperature data showed rather wide scattering, while the various pressure gradients grouped quite nicely. When time was considered as a factor in all of these graphs, only the wind speed-altimeter setting gradient curve had the features mentioned on pages 18 and 20 and shown in Figure 6.

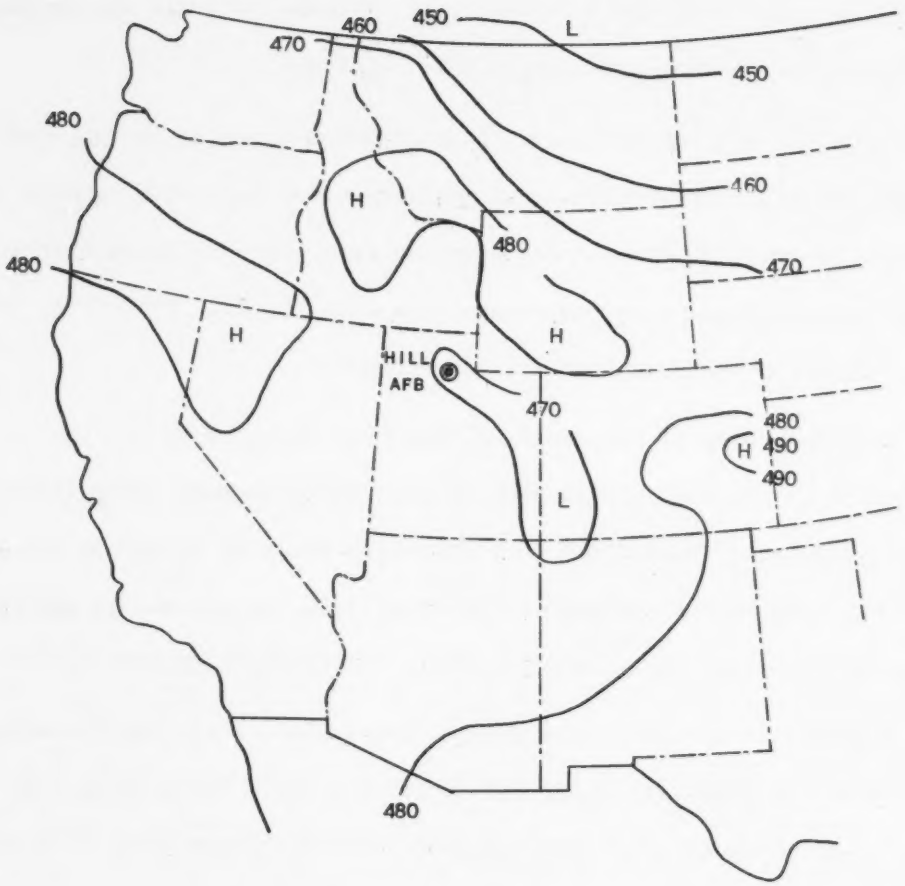

FIGURE 12. NEAR TIME OF EAST WIND TERMINATION. 850 MB CHART FOR 27 JANUARY, 1957. 1130M.

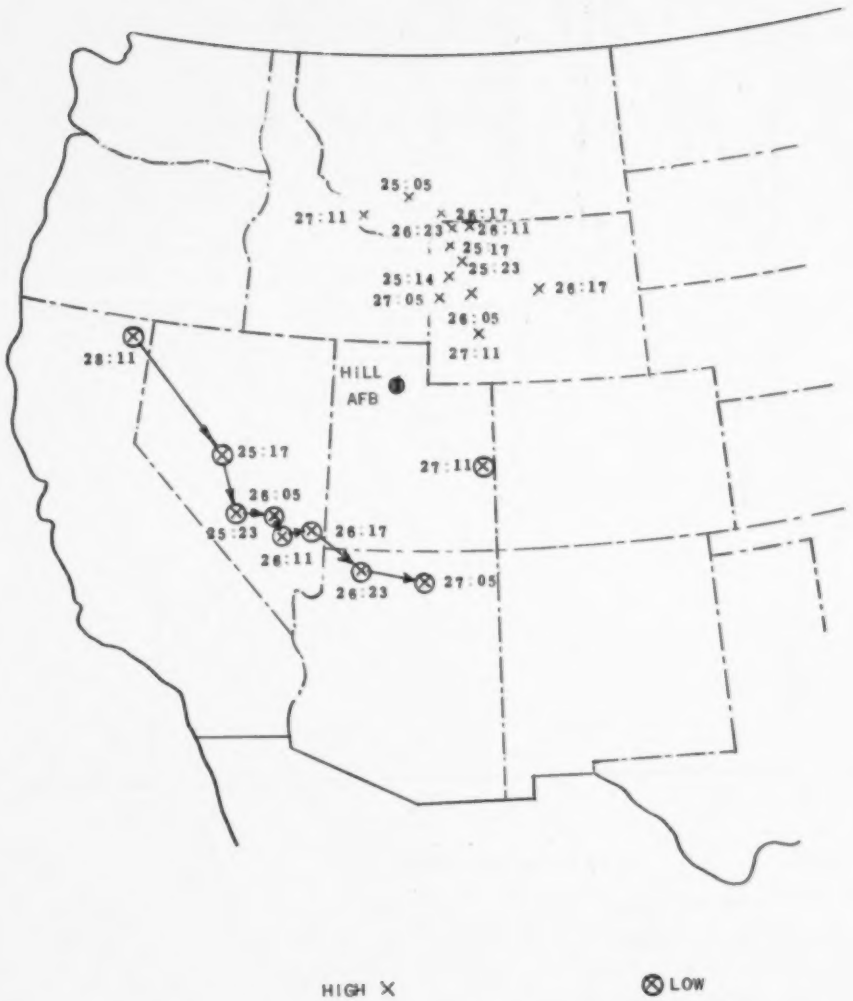

FIGURE 13. POSITIONS OF 850 MB HIGHS AND LOWS AT 6 HOUR INTERVALS FOR 25-27 JANUARY, 1957.

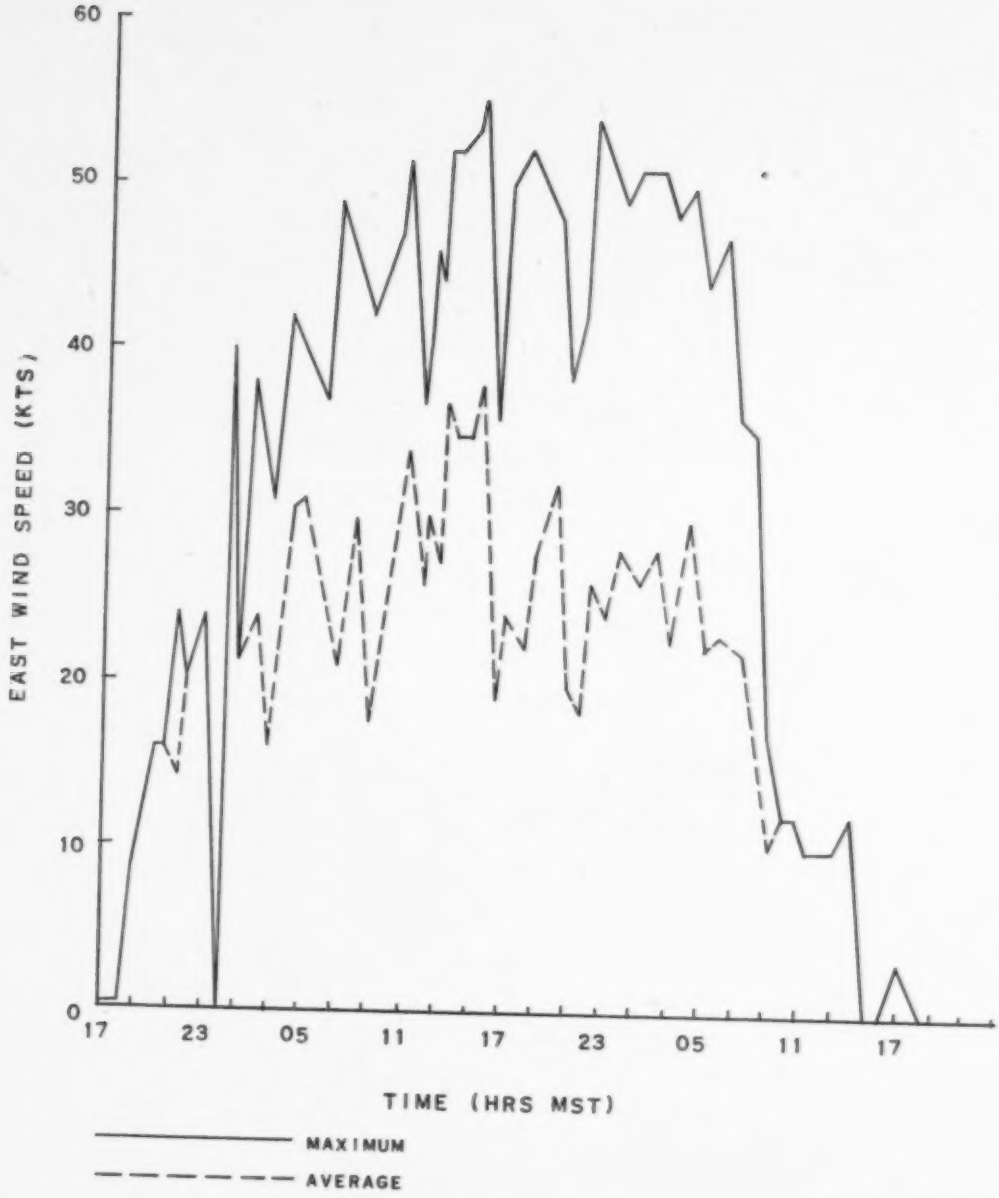

FIGURE 14. TIME DISTRIBUTION OF EAST WINDS AT HILL AIR FORCE BASE (25-27 JANUARY, 1957).

Figure 15 shows the 3-hour positions on the wind speed vs. altimeter setting gradients for Rock Springs minus Hill Air Force Base, Several other stations were substituted for Rock Springs, and the resulting curves were quite similar to Figure 15.

Further examination of the 850 mb maps showed that while the winds were strong, the contour lines were oriented west-northwest - east-southeast, and were rather tightly packed, indicating strong geostrophic flow. As the low pressure center moved east, the gradient decreased, and the wind speeds dropped.

It should be pointed out that, while the high pressure area was present before, during, and after the strong east winds, it was the movement of the low pressure center which seemed to be associated with the wind speeds.

CONCLUSIONS

This study of canyon winds has included many of those factors which most meteorologists consider important for such a phenomenon. While the statistical results strongly suggest that an objective forecasting procedure using these factors is not satisfactory, the results and conclusions of this study will certainly help to point the way for future research on this problem.

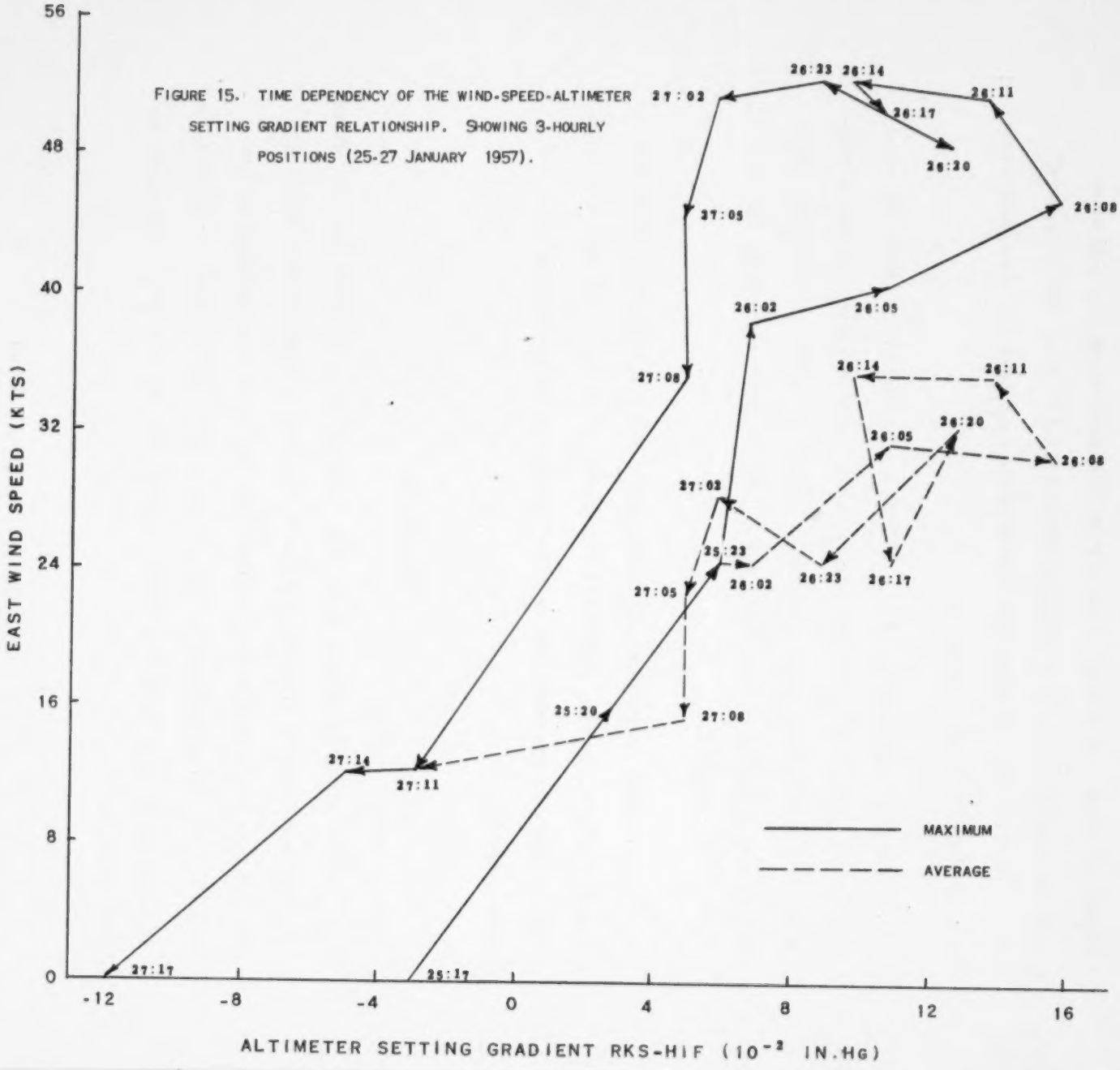
FIGURE 15. TIME DEPENDENCY OF THE WIND-SPEED-ALTIMETER SETTING GRADIENT RELATIONSHIP. SHOWING 3-HOURLY POSITIONS (25-27 JANUARY 1957).
EAST WIND SPEED (KTS)
ALTIMETER SETTING GRADIENT RKS-HIF (10^{-2} IN.HG)
MAXIMUM
AVERAGE
56
48
40
32
24
16
8
0
-12
-8
-4
0
4
8
12
16
27:02
26:23
26:14
26:11
26:17
26:20
26:08
27:05
26:05
26:02
27:08
26:14
26:11
26:20
26:05
26:08
27:02
25:23
26:02
26:23
26:17
27:05
25:20
27:08
27:14
27:11
27:17
25:17

The primary conclusions of this study can be summarized as follows:

1. Moderate wind speeds (20-35 knots) are usually associated with small-scale circulations. This small-scale circulation is of smaller areal extent than the available network of stations, and therefore will not be apparent in the gradients used in this study.
2. Thermally-induced circulation must be separated from the large-scale circulation.
3. No single pair of stations as used in this study gave satisfactory results.
4. The use of lagged data, unless coupled with some other procedure (such as indexing), will usually produce unsatisfactory forecasting results.
5. Seasonal separation of data is desirable.
6. Some type of pressure center indexing system would be desirable.
7. Further work must be done before a satisfactory forecasting procedure and a thorough explanation of these strong easterly canyon winds are possible.

FUTURE RESEARCH

As a prerequisite to any future work on this problem, much more data must be gathered. Large samples from every month should be studied in order to establish a seasonal trend. It is reasonable to assume that there is a seasonal variation of surface friction, and the variation in vegetation is certainly a function of season. There is also a change of

synoptic situation from season to season which may have some bearing on the occurrence of strong canyon winds.

The primary step in any future work on the canyon breezes is to separate the mountain breeze from the large-scale circulation. It is apparent that the majority of cases of winds above 20 knots results from thermally-produced circulation. Care must be taken to separate the winds of each cause, for the temperature-induced local winds, when distinct, will bear little relationship to the synoptic patterns. Such a separation would probably involve reference to synoptic charts.

A further use of the synoptic maps is that of devising a better indexing system. Upper air as well as surface charts should be indexed. Private weather consultants and several Weather Bureau and Air Force forecasters feel that the 850 mb chart gives better results in wind forecasting than does the sea level pressure chart. Since 850 mb-height data are available every 3 hours, an indexing system for 850 mb charts might prove very valuable.

The orientation of isobars and contour lines should be studied in more detail. The relationship between observed canyon winds and the existing geostrophic and gradient winds should also be examined, and should include upper air as well as surface winds.

Previous work on the canyon wind problem [14] suggests that a study of the pressure tendencies would contribute some valuable information. The isallobaric field is indicative of the development of a ridge of high

pressure or a low pressure trough. The isallobars might also be related to the duration of these strong winds, a problem which is almost as important as their velocities. The interrelationships among wind speed, duration, rates of motion of the pressure systems, and the pressure tendencies should also be studied.

Another factor which might be important is the effect of vegetation. Vegetation reduces the velocity somewhat and raises the maximum wind speeds to a higher level above the ground. Studies should be made to see if the seasonal change in vegetation at and around Hill Air Force Base has a significant effect on the winds recorded at the anemometer.

One researcher [18] has suggested that the stability of the air mass is a point worthy of study. Air mass stability is one factor which would be useful in determining whether or not the strong canyon winds will spread out over the valley or be confined to the canyons and their mouths. It has been observed that the easterly circulation sometimes extends above the mountain ridges, as seen by the direction of cloud movement and by the blowing snow (in winter). At other times, strong easterly canyon winds are present while the clouds are moving from west to east. In the latter case the winds will likely be confined to the canyon mouths and the immediate vicinity, while the former is typical of the widespread easterly winds throughout the valleys.

Other writers have made attempts to evaluate the effects of slope and friction in the mountain and valley wind system [4, 7, 8]. The author

believes that these factors are important in the cause of the bubble-like flow of air out of the canyons. No attempt was made to evaluate either term here, but this should be done in any complete study of this phenomenon.

One other item which acts as a modifying agent to the east winds is the variation in type and amount of cloud cover. While not directly associated with the occurrence of strong canyon winds caused by large-scale circulation, the cloud cover probably can affect the maximum wind speed.

Several other factors, such as the influence of the Coriolis force, the height to which cooling extends, the net outgoing radiation from the ground, and turbulent heat conduction [8], must be considered in any thorough study of the canyon winds. Such completeness is beyond the scope of this paper.

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